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Municipal solid waste landfills as geothermal heat sources

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ABSTRACT

It is well established that ground-source heat pumps (GSHPs) require less external energy input than conventional heating and cooling systems for buildings because they exchange heat with the subsurface soil and rock, which has a steady temperature compared to that of the outside air. To address barriers to implementation for GSHPs, incorporation of heat exchangers into civil engineering infrastructure is being investigated to reduce installation costs. Of these infrastructures, municipal solid waste (MSW) landfills may be a potential source of heat for GSHPs due to their elevated temperatures associated with the long-term, exothermic decomposition of organic materials within the waste. To assess this potential, this paper provides a review of studies focused on characterization of the thermal resource of landfilled MSW. Further, the potential impacts of heat exchange on rates of methane generation, hydraulic performance of landfill liners, and clogging of leachate collection systems are evaluated. Based on landfill construction requirements and different approaches for GSHP installation used in practice, configurations for geothermal heat exchangers in landfills are proposed for different landfill operational and closure scenarios. An economic analysis of geothermal heat exchange in MSW landfills indicates that they are expected to provide an accessible and sustainable thermal energy resource.

Contents

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1. Introduction

Commercial and residential buildings consume approximately 39% of the primary energy in the U.S., which corresponds to the generation of nearly 43% of the U.S. carbon emissions [1]. Development and characterization of new technologies to reduce building energy consumption are important goals for the U.S., as well as around the world, from both economic and environmental perspectives. Of the energy used by buildings, heating and cooling systems account for approximately 20%, emphasizing the need to improve their efficiency.

Ground-source heat pumps (GSHPs) are a commonly used technology to supplement heating and cooling systems for buildings by using subsurface soil and rock as a heat source or sink [2]. Although GSHPs have a relatively high efficiency compared to other heating and cooling technologies, which has been verified through field tests [3], and also have a relatively mature set of tools available for their design [4], their high up-front installation costs have been identified as a barrier to their wide-spread implementation [5]. Efforts have been made recently to incorporate ground-source heat exchangers into different civil engineering infrastructure in order to reduce installation costs and to use infrastructure for multiple purposes [6,7]. In these cases, the incorporation of a ground-source heat pump system represents only a small fraction of the overall cost of the civil engineering infrastructure [8,9]. Examples of thermally active civil engineering systems include building foundations, retaining walls, tunnel linings, pavements, and sewers [7]. Of these approaches, implementation of GSHPs into building foundations (i.e., energy piles or energy foundations) has been widely adopted throughout the world, including both successful pilot test projects [9–11] and implementation into buildings throughout the world [6,12–14].

Another opportunity to enhance the implementation of GSHPs is the exploitation of man-made heat sources which may provide greater thermal energy than the subsurface soil and rock. Specifically, this paper focuses on the potential of using municipal solid waste (MSW) landfills as a thermal resource. On average, the encapsulated waste mass in landfills will sustain temperatures up to 35 °C higher than that of the surrounding subsurface due to the exothermic decomposition of organic materials [15–20]. Modern landfills already incorporate several complex plumbing systems to collect leachate, detect leaks, vent landfill gas, or recirculate leachate to accelerate methane production in bioreactor landfills [20], so the inclusion of additional plumbing for heat exchange would not lead to a significant increase in cost or complexity. The objectives of this paper are to summarize relevant results from studies which characterize the thermal resource of MSW landfills; to evaluate the implications of heat exchange on gas generation and performance of various landfill components; to evaluate the cost implications of landfill heat exchange, and to outline possible configurations for landfill heat exchange systems for landfills at pre- and post-closure stages.

2. Background on ground source heat pumps

GSHPs have undergone a steady improvement in installation techniques and heat pump infrastructure since they were first developed by the Austrian mining engineer, Peter von Rittinger, in 1855 [6]. Although there are many types of GSHP systems, this study is focused upon closed-loop GSHP systems which incorporate three subsystems: a closed-loop network of heat exchangers in the ground, a heat pump containing a low boiling point refrigerant, and a heat distribution network within the building. The heat exchangers in GSHPs are typically high-density polyethylene (HDPE) or high-density polybutylene (HDPB) tubing, and can be installed vertically within a borehole or horizontally within a trench.

A typical heat pump cycle in heating mode is shown in Fig. 1. Thermal energy is collected from the subsurface soil and rock by circulating a mixture of water and antifreeze (typically propylene glycol) through the heat exchange tubing [2–4]. The heat exchange tubing is coupled to the heat pump through a baffled coil which permits transfer of heat from the water-antifreeze

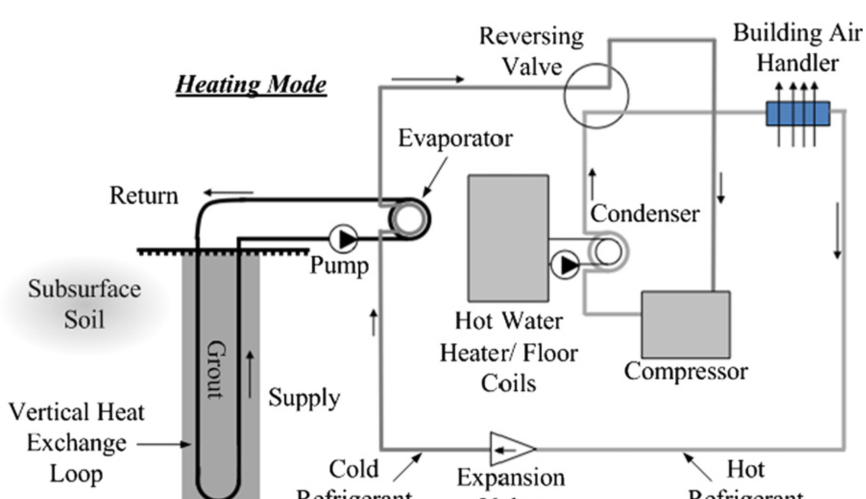

Fig. 1. Schematic of ground source heat pump system.

mixture to the refrigerant circulating within the heat pump. This permits the refrigerant to be pre-heated before entering a compressor, which converts it into a superheated vapor. This heated refrigerant is either stored within a hot water heater or circulated through an air handler or hydronic system within the floors to transfer heat to the building. The refrigerant is then sent through an expansion valve, which causes it to drop in pressure and decreases its temperature. The refrigerant then is repeated by passing the cold fluid through the baffled coil. This process can be reversed to supply cooling to the building [2,6].

GSHPs are more efficient than air-source heat pumps because their heat source or sink (the ground) has a steady temperature compared to the outside air. Throughout most of the world, the subsurface soil or rock below the zone of seasonal influence (6 to 12 m) and up to depths of 100 to 200 m has a relatively steady temperature close to the mean annual air temperature, in the absence of a geothermal gradient [2]. Although GSHPs change the temperature of the subsurface due to heat exchange, this heat can be replenished by conduction if designers select a proper spacing of heat exchangers in the ground [4]. Because the temperature of the heat source or sink is steady, the compressor within the heat pump does not have to operate as frequently as in an air-source heat pump, leading to lower electricity consumption. Lienau [21] collected energy data from 217 residential, school, and commercial buildings and found that GSHPs have an energy savings of 13–60% compared to air-source heat pump systems and 32–53% compared to conventional electric heating systems. Studer and Krarti [22] performed an evaluation using the DOE-2 model for GSHPs in residential buildings located in different climate settings around the state of Colorado, USA, and found that the electricity peak demand, energy use, and CO_2 emissions are 10–30% lower than those for conventional heating and cooling systems.

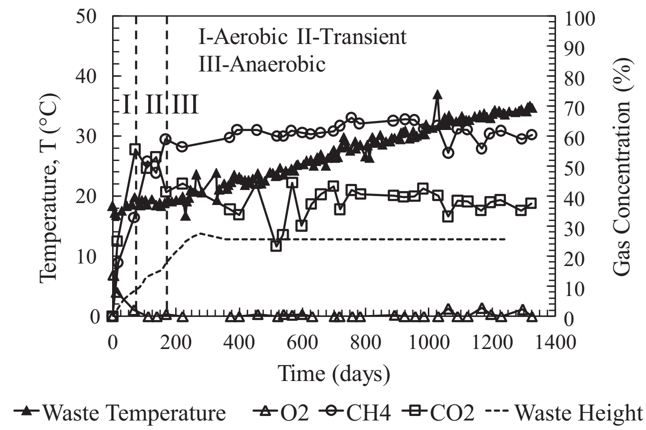

Fig. 2. Heat and gas generation rates [17].

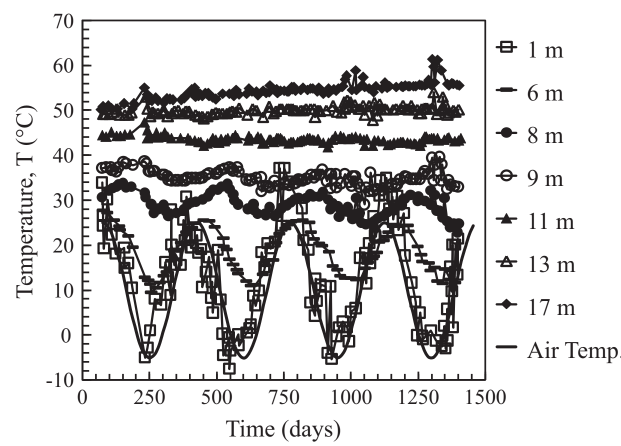

Fig. 3. Variation of temperature at different depths in a Michigan landfill [18].

3. Landfill thermal resources

3.1. Mechanisms of heat generation in landfills

Leachate, gas, and heat are the three most common byproducts of organic waste decomposition in landfills. The decomposition of organic wastes occurs in three phases: an aerobic phase, a transient phase, and an anaerobic phase [15,20]. The initial decomposition of organic wastes occurs under aerobic conditions. However, shortly after waste is buried in the landfill, oxygen availability becomes limited and anaerobic generation of methane and carbon dioxide, the two main components of landfill gas, begins to increase as degradation enters the transient phase [15]. After a peak value of approximately 70% by volume, carbon dioxide concentrations begin to decrease to a stabilized level of approximately 40% by volume as anaerobic conditions are established. Over a similar timeframe, the methane concentration gradually increases and stabilizes at around 60% (Fig. 2). Heat generation is observed to occur during all three phases with the greatest gain in temperature occurring during the onset of anaerobic decomposition [16,17].

To investigate the coupled gas and heat generation during the aerobic, transient, and anaerobic phases of decomposition, Hanson et al. [17] monitored a landfill in Michigan, USA during the placement and storage of new municipal waste. Typical results of the gas and heat production with time after closure are shown in Fig. 2. During the study, the aerobic phase was observed to last from two weeks to three months among various cells at the landfill site. The transient phase occurred from two to five months, followed by the anaerobic phase. Heat generation was measured to be nearly 5 to 10 times higher during the combined transient and anaerobic phase than the initial aerobic phase, which made up for only 20% to 30% of the total increase in temperature during all three phases. Additionally, the temperature increase after placement was observed to be nearly linear and did not correlate to the measured non-linear transitions in landfill gas composition.

3.2. Characteristics of municipal solid waste landfill temperatures

3.2.1. Variation of waste temperature with depth

Yesiller and Hanson [18] placed horizontal and vertical thermocouple arrays within a closed landfill in Michigan, USA to measure the variation of temperature and heat generation with location in the landfill for over a period of several years. These sensor arrays were placed to assess the change in temperature with depth and distance from the cover and landfill cell edge, respectively, in the landfill waste, cover, and bottom liner. Typical results from this landfill are shown in Fig. 3. Yesiller and Hanson [18] observed that waste materials located near the cover (within 9 m depth) were influenced by seasonal temperature variations, with an increasing phase lag occurring with increased depth. Temperatures increased with depth to a maximum of 56 °C at 17 m. Similarly, horizontal arrays of thermocouples indicated that waste near the edge of the landfill cell was more affected by seasonal temperatures while waste further from the cell edge maintained a stable temperature throughout the year.

Similar results were obtained by Yesiller et al. [16], who measured temperatures in four landfills under different climatic and operational conditions. The upper and lower bound (UB and LB)

temperature profiles for these locations are shown in Fig. 4. The normalized depth is the depth of waste located above the temperature sensor divided by the total depth of waste. All locations exhibited a peak temperature (25 to 56 °C) around mid-depth (normalized depth of 0.5) with lower sustained temperatures at greater depths. The findings of these studies suggest that the lower half of the landfill will provide a warmer more stable heat source for heat exchange.

3.2.2. *Effect of waste age on heat content*

Another important concern about heat exchange systems in landfills is the sustainability of MSW temperatures over time. Several studies have investigated the influence of waste age on heat generation [16–19]. In order to separate the heat generated in waste due to exothermic decomposition from that associated with climatic fluctuations, these studies use a variable referred to as the heat content. The heat content is defined as the area between the temperature time series measured for waste at a certain depth and the temperature time series for ambient temperatures expected at that same depth due to heat flow from a seasonal climatic boundary condition (estimated using an analytical model), all normalized by the duration of a measurement period [16]. The variation in heat content with waste age measured by Yesiller et al. [16] and Yoshida and Rowe [19] are shown with representative trends in Fig. 5. The data indicates a rapid increase in temperature of young waste to a peak temperature after 2 to 7 years, followed by a gradual decrease in temperature. Some wastes showed a greater decrease than others, although the waste generally remained warmer than the initial temperature. A similar trend was observed by Hanson et al. [17] who observed a peak in waste temperature at mid-age by measuring stabilized temperatures of 47 °C in 4 year old waste, 56 °C in 7 year old waste, and 47 °C in 13 year old waste at equal depths in a landfill in Michigan, USA.

3.2.3. *Effect of waste placement conditions on heat content*

Yesiller et al. [16] found that waste placement conditions can impact the heat content of the waste. These placement conditions include the initial waste temperature and waste placement rate. The results in Fig. 6 indicate a strong positive correlation between initial waste temperature and heat content. Waste placed during warmer seasons was observed to reach higher maximum temperatures than similar wastes placed during colder seasons. Additionally, a positive correlation between heat content and waste placement rate was observed [16,23]. Waste placed at a higher rate was found to reach higher overall temperatures, as shown in Fig. 7. As seasonal fluctuations within the waste were observed to reduce significantly after the placement of the first lift of 4–5 m, a faster waste placement rate reduces the amount of seasonal exposure [16]. A more sustained generation of heat occurs in waste which is placed slowly. Both observations indicate that landfill operation can be optimized to maximize the temperature conditions for geothermal heat exchange.

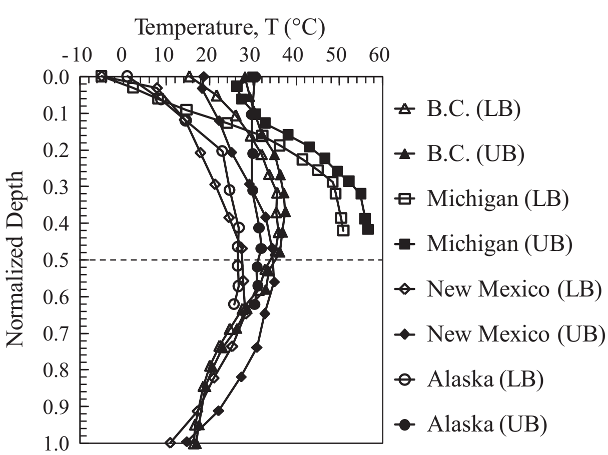

Fig. 4. Typical temperature profiles [16].

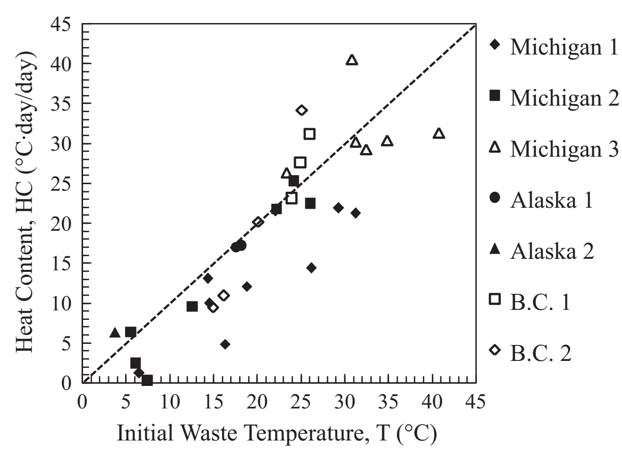

Fig. 6. Variation of heat content with initial waste temperature [16].

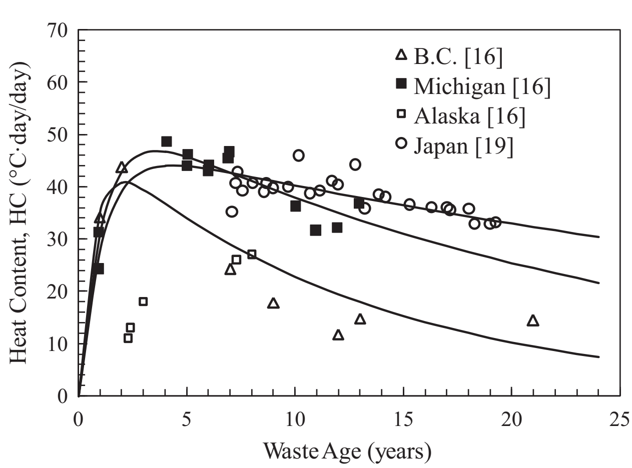

Fig. 5. Trends in heat content with waste age [16,19].

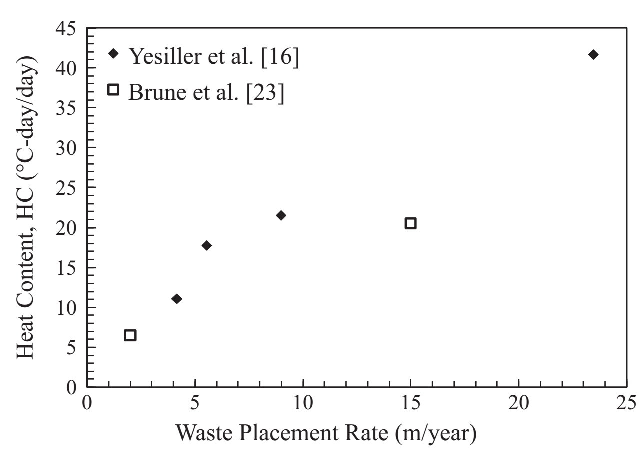

Fig. 7. Variation of heat content with waste placement rate [16,23].

3.2.4. Effect of climatic conditions on heat content of waste

Yesiller et al. [16] also analyzed the effects of climatic conditions (characterized by average yearly air and earth temperatures and yearly precipitation rates) on temperature and heat content to understand the possible influence of landfill location. Average yearly air and earth temperatures were not observed to influence the heat content recorded in the waste; however, the precipitation rate was found to affect the heat content of MSW before closure. The upper and lower bound heat content values measured at a landfill in Michigan are shown in Fig. 8 as a function of average daily precipitation. The heat content increases with the precipitation rate, with a peak value occurring at a precipitation rate of 2.3 mm/day. This trend suggests that the MSW may have an optimal water content at which the waste will have a maximum heat content. Once the precipitation rate is increased past the optimal value, the additional water may not contribute any further to the generation of heat, leading to a decrease in heat content.

3.3. Thermal properties of MSW

To properly design an efficient geothermal heat exchange system within a landfill, several key material properties must be quantified for heat flow analysis. These properties include the unit weight (γ), thermal conductivity (k_t), volumetric heat capacity (C), and thermal diffusivity (α) of in-place MSW. Only limited information has been reported concerning these material properties. Hanson et al. [24] defined thermal properties of MSW from four landfill sites located within the USA (Table 1). These properties were observed to vary with waste placement conditions, leachate collection operations, and waste constituents. Additionally, both k_t and C were found to increase with increasing γ and water content of the MSW.

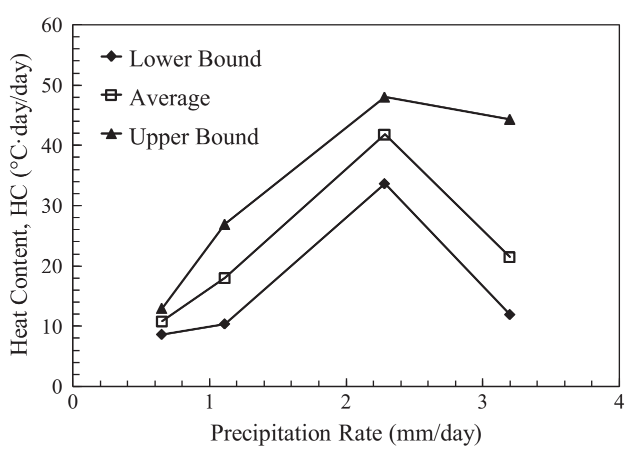

Fig. 8. Variation in heat content with average daily precipitation [16].

Table 1
Thermal properties of MSW [24].

Material property	Range
γ (kN/m^3)	5.2–9.8
k_t (W/m K)	0.3–1.5
C (kJ/m^3 K)	1000–2200
α (m^2/s)	3×10^{-7}–7×10^{-7}

4. Impacts of heat on landfill performance

Prior to implementation of geothermal heat exchange technology at a planned or existing landfill, the potential effects of changing the temperature of the waste on the different processes (e.g., methane gas generation, waste settlement) and control systems (e.g., hydraulic barriers, leachate collection systems) in the landfill must be understood. Depending on the design goals of the heat exchange system, heat may be withdrawn or injected into the landfill. Although it is likely that GSHP systems in landfills will be most suited for extracting heat to use in buildings, they can potentially be used to control the temperature of the waste to affect different processes.

4.1. Impact of temperature on methane gas generation

Several studies have investigated the use of temperature control to optimize the rate of methane generation within a landfill after closure [25,26]. The motivation of these studies was to optimize methane generation and collection for the purpose of generating electricity through combustion. Hartz et al. [25] measured gas concentrations in cylindrical samples of MSW obtained from various landfill sites in New York and California, USA at different temperatures. They observed an optimum temperature for methane gas production at approximately 41 °C (Fig. 9). The results in Fig. 9 suggest that temperatures above 41 °C result in a decrease in methane generation, with complete cessation in methane generation around 55 °C. However, as the temperature range of most landfills has been observed to be significantly below 40 °C [16–19], it is expected that an installed geothermal heat exchange system would permit temperatures to be maintained in the increasing portion of the trend in Fig. 9. In this case, methane generation will increase with increasing temperature up to the optimum value. However, the concern remains that methane generation rates may drop rapidly if using a landfill as a heat sink which could force the internal temperature above the threshold value of about 40 °C.

4.2. Impact of temperature on landfill settlement and stability

It is important to understand whether temperature changes induced by geothermal heat exchangers within a landfill would impact the mechanical and hydraulic properties of the encapsulated waste. Edil et al. [27] summarized several factors which influence the settlement of landfills with time, which include initial waste density, type and amount of decomposable materials within the waste, fill height, stress history, leachate levels, and

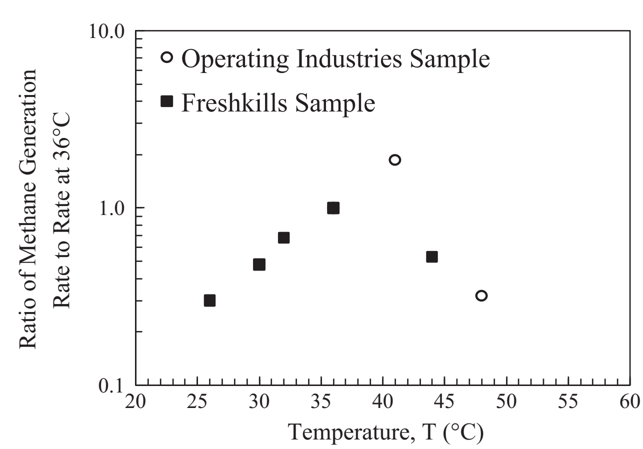

Fig. 9. Methane generation with temperature [25].

additional environmental factors including water content and temperature within the waste body.

Lamothe and Edgers [28] studied the effect of several environmental parameters such as water content, age, and temperature on the one-dimensional vertical settlement of MSW. Compression tests were performed on eight specimens of MSW (Fig. 10), five at 20 °C (Samples 1, 3, 4, 7, and 8) and three at temperatures ranging from 30 to 35 °C (Samples 2, 5, and 6). In the study, vertical strain was defined to occur in three different stages: initial, delayed, and decompositional. Initial compression of void spaces and soft materials was found to occur rapidly after placement. Delayed compression occurs due to the re-orientation of particles to a more stable structure at a constant effective stress. Delayed compression is shown in Fig. 10(a) as the first initial linear strain trend within the waste specimen. Finally, decompositional compression occurs during the decomposition of waste solids within the waste mass. Decomposition results in a decrease in solid materials, weakening the waste structure and resulting in a faster rate of compression. Because decomposition may occur more rapidly at higher temperatures, more settlement may occur (as suggested in Fig. 10). Overall, greater settlement was observed for wastes at higher temperature [Fig. 10(b)]. Additionally, increased temperatures lead to an increase in the compression index (rate of vertical strain with time) during both the delayed and decomposition phases of compression, potentially due to an increase in biologic activity with heat [28]. Heat exchangers in waste may also be used to decrease the temperature of waste by extracting heat, potentially resulting in less settlement.

4.3. Impact of temperature on landfill components

4.3.1. Impact of temperature on landfill base liners

Many landfills utilize geomembranes and geosynthetic clay liners (GCLs) as components of the primary base liner [20]. These liners serve as an integral part of the landfill containment system as they prevent leachate from exiting the landfill cell and contaminating groundwater. If liner temperatures were to be elevated through proximity to organic waste decomposition, this could result in desiccation of secondary clay liners or mineral components within a GCL, loss of performance, and increased contaminant diffusion through base liners [29–34].

Elevated temperatures at the base of a landfill also have the potential to create thermal gradients between the landfill base liner and the underlying groundwater regime, causing increased water flow from the landfill to the underlying subsoil and potentially resulting in desiccation of compacted clay or GCL mineral components of the base liner [29]. To analyze the impact of thermal gradients on water flow and potential desiccation of GCLs in a composite liner system, Southen and Rowe [29] performed heat flow tests on two combinations of GCLs and underlying compacted subsoils placed in a cylindrical mold. Samples were heated to obtain a representative thermal gradient until a steady-state water-content profile within the soil-GCL column was attained. Typical final gravimetric water content profiles are shown in Fig. 11(a) for different values of initial subsoil water content. Southen and Rowe [29] observed that the initial subsoil water content had a major impact on the final

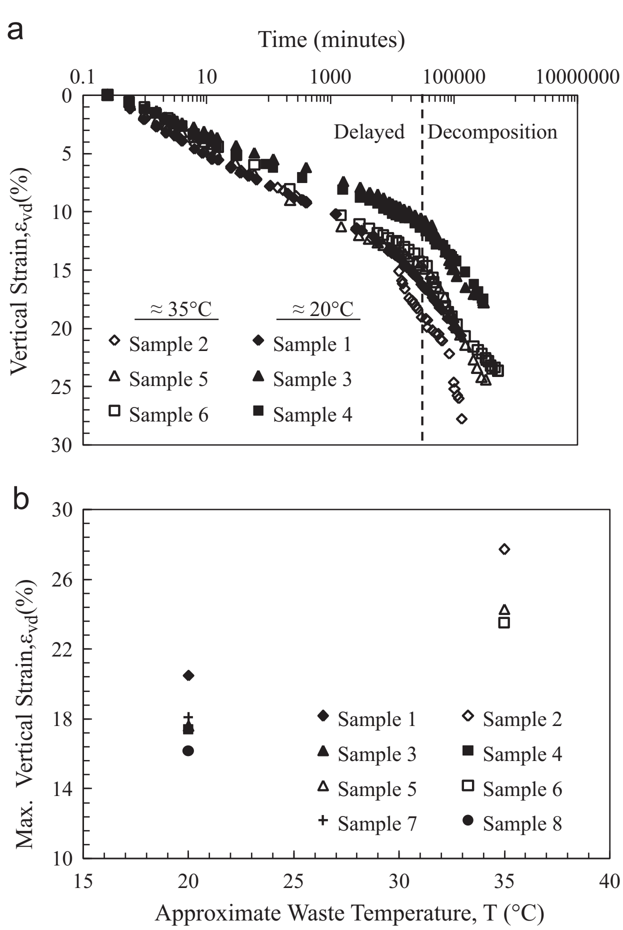

Fig. 10. Vertical settlement of MSW data showing: (a) Delayed and decomposition phases of settlement; (b) Settlement at end of testing against waste temperature [28].

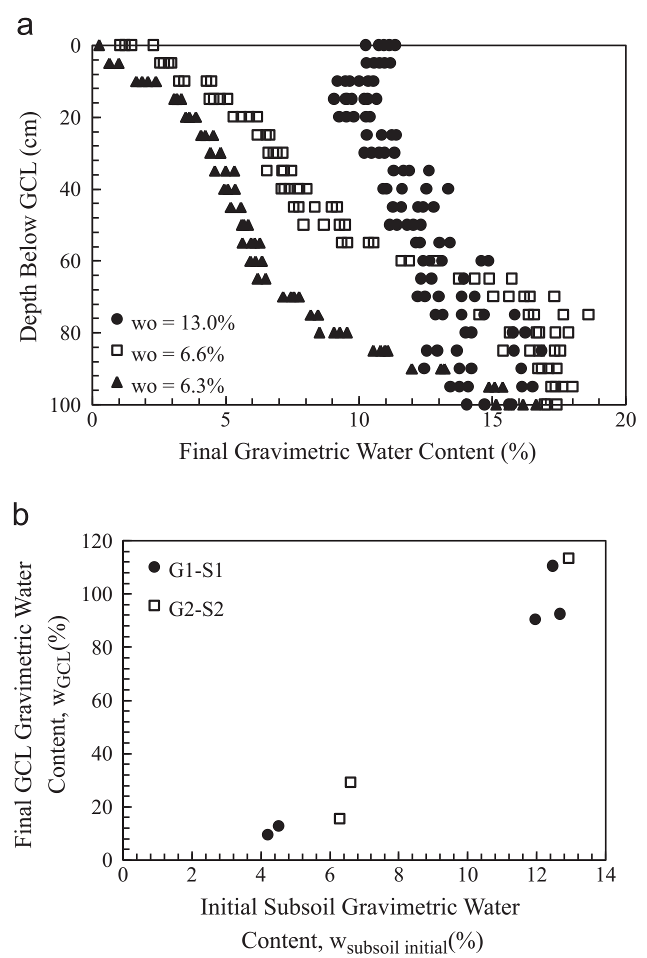

Fig. 11. Effect of initial subsoil water content on: (a) Steady-state water content profiles in heat flow tests; (b) Final GCL water contents [29].

water content within the GCL. Tests performed for lower initial subsoil water contents resulted in a nearly dry GCL, as shown in Fig. 11(b) while tests performed at higher initial subsoil water contents kept the GCL relatively moist and undamaged.

The influence of the thermal gradient on the final water content of the GCL with time is shown in Fig. 12. The rate of water movement within the GCL system increased with increasing thermal gradient, indicating that higher landfill liner temperatures may result in increased desiccation of the mineral liner in a smaller period of time. Due to desiccation, Southen and Rowe [29] found that the hydraulic conductivities of the damaged GCLs had increased 3 to 4 times in magnitude. These findings indicate that geothermal heat extraction from the base of a landfill may be useful in minimizing the thermal gradient across the liner system. A geothermal heat exchange system placed close to the base of a landfill constructed with a GCL over relatively dry subsoil may therefore be effective at minimizing water flow and potential desiccation.

Elevated temperatures may also have adverse effects on the hydraulic properties of the clay mineral components of GCLs or compacted clay, as well as on the diffusion coefficient of the geomembrane component of the primary liner [30]. The results in Fig. 13 indicate that the advective and diffusive flow through the liner are 30% and 40% higher, respectively at 20 °C compared to their values at 10 °C, and 80% to 100% higher for a temperature of 35 °C. In addition to the decreased performance of landfill liner systems due to elevated temperatures, a decrease in service life of the liner has also been observed. According to Viebke et al. [31] and Bonaparte et al. [32], the service life of a typical HDPE geomembrane is expected to be approximately 600 years when exposed to a maximum temperature of 20 °C, but only 160 years when exposed to a maximum temperature of 35 °C. Further, the service life may decrease to less than 50 years if exposed to temperatures between 50 to 60 °C. If heat is extracted from the base of a landfill using a geothermal heat exchanger, the lifetime of the liner system may potentially be extended.

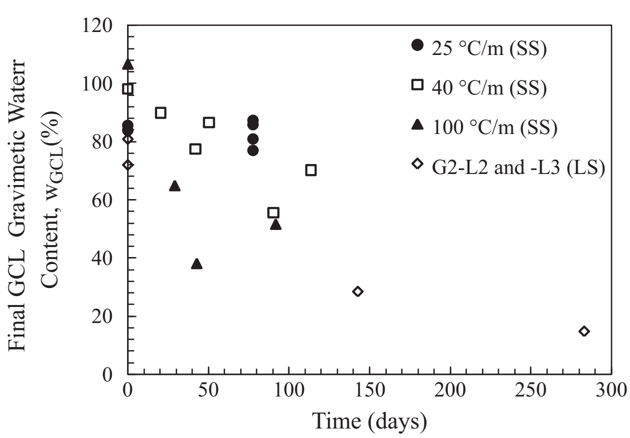

Fig. 12. Final GCL water content for different thermal gradients (SS-small scale; LS-large scale) [29].

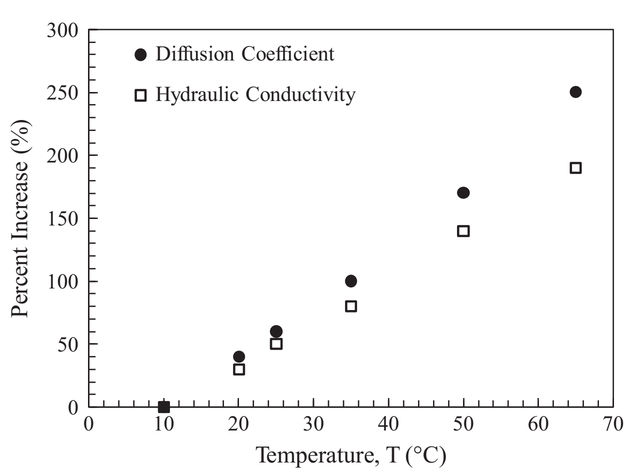

Fig. 13. Temperature effects on the advective and diffusive properties of a clay liner system [30].

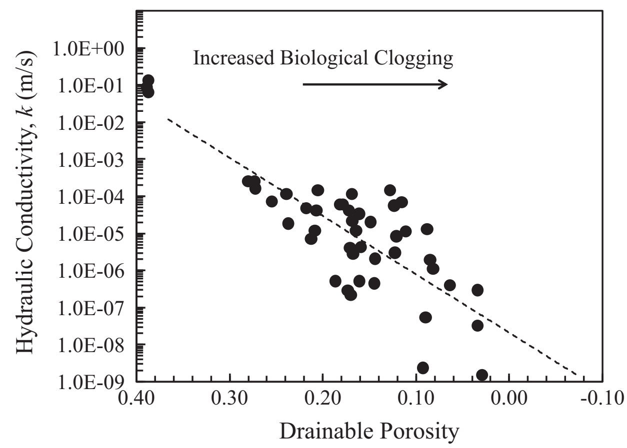

Fig. 14. Decrease in hydraulic conductivity with biological clogging [30].

4.3.2. *Impact of heat on leachate collection systems*

The leachate collection layer above the landfill base liner in MSW landfills is used to collect leachate from the waste and divert it to a sump for collection. The leachate is collected to minimize leachate mounding and the potential for greater hydraulic heads on the liner. Rowe et al. [35] and Rittman et al. [36] found that the primary reason for clogging within a leachate collection layer with a properly installed geotextile filter is bacterial growth within the leachate. Rowe et al. [35] passed leachate from multiple landfill sites through a cylindrical column of 6 mm glass beads to illustrate the effect of biological clogging on the hydraulic conductivity of a granular drainage layer. The porosity of the glass beads tended to decrease with increasing biological activity, resulting in a decrease in hydraulic conductivity as shown in Fig. 14.

Elevated temperatures have been observed to increase the rate of biologic activity within waste [25,37]. This suggests a higher potential for partial clogging of the leachate collection layer due to elevated temperatures. If enough clogging is developed to significantly decrease the hydraulic conductivity of the drainage layer, leachate will begin to mound at the base of the landfill. Again, geothermal heat exchangers may be a useful tool to decrease temperatures in the landfill and minimize the adverse effects of increased biological activity in the leachate collection layer.

5. Design of geothermal heat exchangers

5.1. *Conditions required for efficient use of landfill-source heat exchangers*

One of the objectives of geothermal heat exchange systems in landfills is to exploit regions of high temperature. However, it is also important to place heat exchangers in regions with high thermal conductivity. Although the results in Table 1 indicate that

the thermal conductivity of MSW is particularly variable, higher thermal conductivity can be expected in waste with a higher degree of saturation. Suction values in the water retention curves defined by Breitmeyer and Benson [31] for different waste materials were interpreted in Fig. 15 in terms of their height above the leachate collection layer. The data in this figure indicate that the waste is able to retain water up to several meters above the leachate collection layer. The fact that the waste does not drain to a degree of saturation close to zero suggests that the thermal conductivity may not reduce significantly with height above the base liner.

5.2. Design of heat exchange systems in landfills

Closed-loop heat exchange systems can be arranged in either a horizontal or vertical configuration [4,39,41–43]. Typically, horizontal systems are installed in loops within a large surface area located only a few meters beneath the soil surface. By placing these horizontal loops in an overlapping "slinky" formation, the surface area required for heat exchange can be reduced. Vertical configurations are installed within boreholes that can reach in excess of 100 m beneath the soil surface [4]. Single or double "U-tubes" are placed within the boreholes and the remaining space is backfilled with sand, bentonite, or thermally enhanced grout. Generally, a horizontal configuration will be favorable for smaller building systems requiring mostly heating with a large available surface area for installation, while a vertical configuration will benefit larger systems requiring both heating and cooling with little available surface area.

More specifically, the adoption of either a horizontal or vertical configuration will require the consideration of the following factors: the geology and hydrology of the subsurface, available area for installation, behavior of the heat source, and the heating and cooling demand required from the heat exchange system [4,39]. However, for the design of heat exchange within an MSW landfill, the engineer must also consider whether a cover system has already been placed on the landfill (closed), as well as size of the landfill, progress of waste placement, and existence of intermediate leachate or gas collection systems located within the body of the landfill [20]. Table 2 includes a summary and comparison of potential heat exchanger configurations for MSW landfills in pre- and post-closure stages.

For a closed landfill, only a vertical heat exchange configuration can be installed through the cover system. Such a system requires the drilling of multiple vertical boreholes through the crest of the landfill toward the base of the landfill [Fig. 16(a)]. However, the boreholes should not extend too deep to avoid

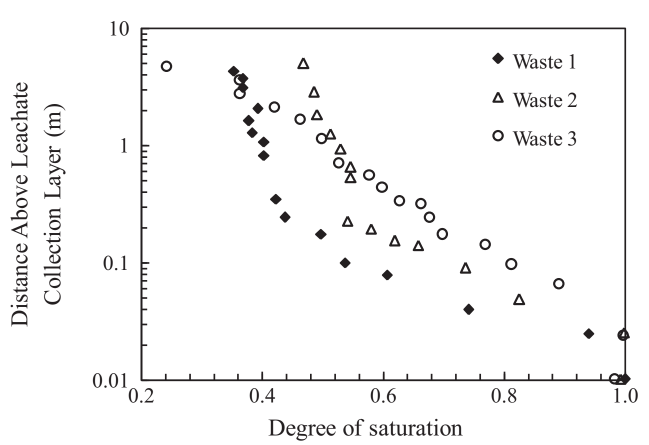

Fig. 15. Typical water profile of different wastes above leachate collection layer [38].

Table 2
Comparison of different potential heat exchange configurations.

Stage of closure of landfill cover system	Heat exchange configuration	Connection system	Collector material	Advantages	Disadvantages	Suggested application
Post-closure	Vertical loop	Above-cover connection	HDPE or HDBE tubing	Can be utilized for landfills whose cover has already been installed	Punctures through landfill cover system, may interfere with intermediate leachate collection systems, tedious installation process	Landfills that have already been closed by could serve as a suitable heat source
Pre-closure	Vertical loop	In-waste connection	HDPE or HDBE tubing	Requires less pipe length, requires least amount of energy input to the pump, promotes even heat distribution and settlement through the MSW	Increased drilling/installation costs, cannot be utilized by landfills with intermediate leachate collection systems	Taller landfills with reduced surface area or those that have already begun waste placement
	Horizontal loop	Parallel	HDPE or HDBE tubing	Easier installation, reduced cost	Increased time span of installation, potential damage to installed loops during settlement and waste placement	New landfills with large surface area that have not begun waste placement
	Horizontal "Slinky"	–	HDPE or HDBE tubing	Requires less surface area, increased amount of heat exchange in smaller areas	Could promote differential settlement and heating of MSW, potential for progressive cooling of waste material due to excessive heat exchange, requires more piping, higher pumping energy input required than other horizontal configurations	New landfills with less available surface area that will be utilized as an alternating heat source and sink throughout operation
	Horizontal "direct expansion"	Parallel	Copper tubing	Increased efficiency, reduced length of pipe required, requires less power input into the heat pump, eliminates use of circulating pump	Susceptible to corrosion from landfill wastes, increased cost of pipe material	Not recommended for use due to the potential for pipe corrosion

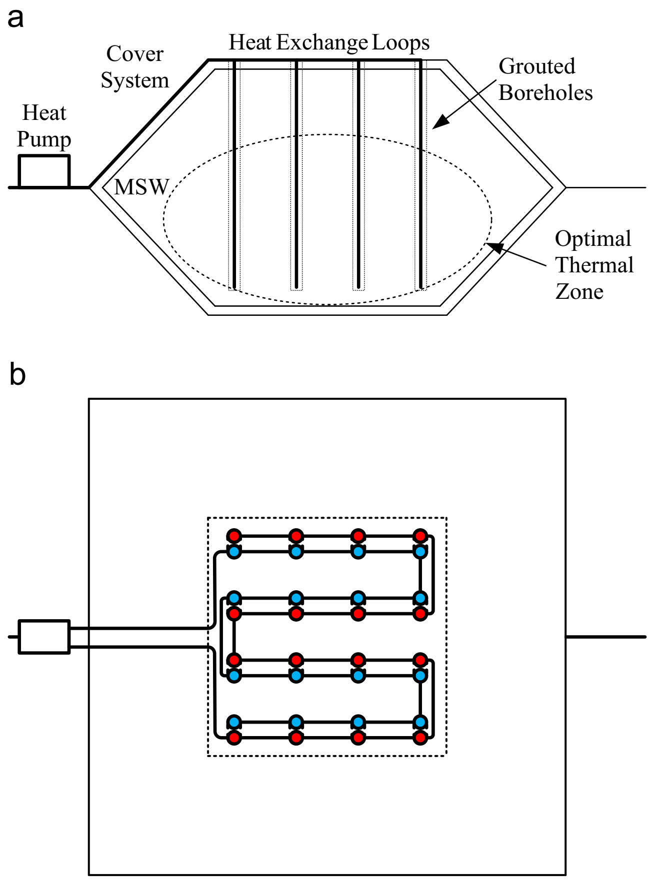

Fig. 16. Vertical geothermal heat exchanger configuration for closed landfills: (a) Elevation section of vertical configuration; (b) Plan view of vertical configuration.

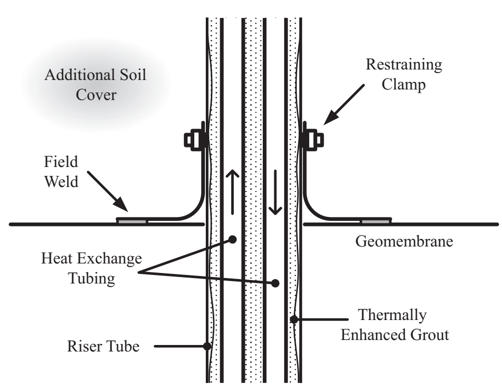

Fig. 17. Vertical heat exchange tubing at location of cover system geomembrane [14].

damage to the landfill liner and leachate collection system. This system has the disadvantage that a borehole must be drilled through the cover system, therefore puncturing the hydraulic barrier (which commonly includes a geomembrane [20,40]). To maintain a continuous seal between the cover and heat exchange system, an additional piece of geomembrane must be welded or seamed onto the existing undamaged geomembrane and clamped to a riser tube centered against the original cover geomembrane, as shown in Fig. 17 [40]. This process requires removal of the soil cover immediately surrounding the location of the borehole for the welder to reach the existing geomembrane. Once sealed, the soil cover is replaced surrounding the riser tube and the heat exchange tubing (either high density polyethylene or polybutylene) will be placed into the borehole. All remaining space is filled with a thermally enhanced grout in order to reduce gaps and to increase heat exchange between the circulating fluid and surrounding MSW [41]. Gate valves should be installed on each heat exchange tube in order to verify uniform flow within each individual loop. Further, each borehole will be directly connected to one another at the surface of the landfill cover, as a manifold connection nearest the heat pump would develop unnecessary pipe congestion. Horizontal spacing between boreholes will depend on the heating and cooling demands of the recipient structures, as well as the thermal properties of the MSW [4] [Fig. 16(b)]. Though expensive, due to the tedious installation process, this type of configuration would be suitable for closed landfills that meet the required thermal demands; however, this is not suggested for closed landfills with intermediate leachate or gas collection systems located within the body of the MSW due to potential interference caused by the drilled boreholes.

For relatively new open landfills, more heat exchange configurations are available for implementation depending on landfill progress, leachate and gas collection design, and size. For taller MSW landfills of smaller width, a vertical loop configuration may installed. This configuration is similar to the design of vertical heat exchange for the closed landfill, where HDPE or HDBE tubes are placed and grouted within boreholes drilled into the MSW. However, in this case, the top of each borehole will start deeper within the MSW, at a nominal depth of around 0.25. By doing so, no intrusions are made into the landfill cover system and the heat exchange is allowed to operate in the optimal thermal zone, where stable temperatures and moister waste conditions exist

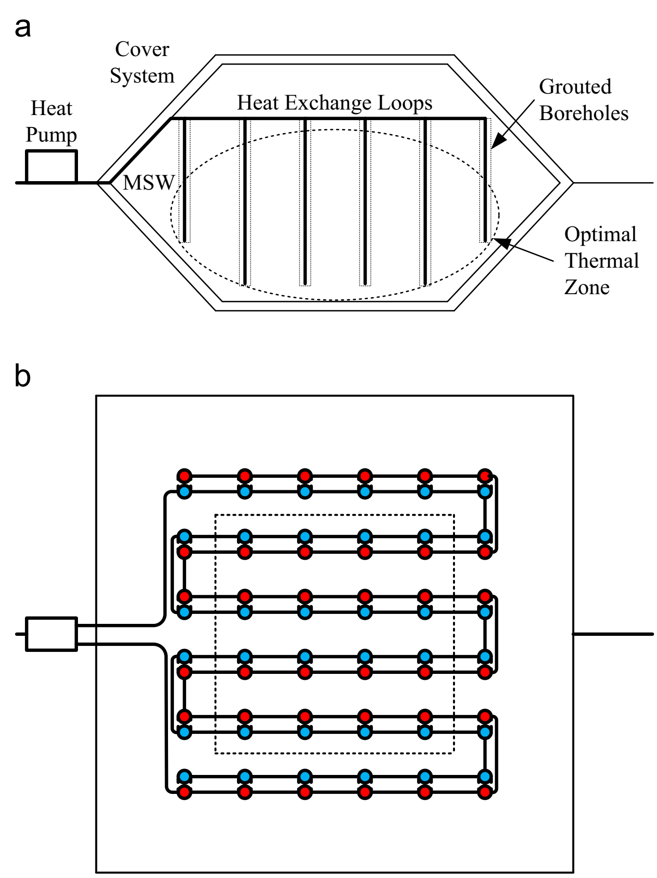

Fig. 18. Vertical geothermal heat exchanger configuration for new landfills: (a) Elevation section of vertical configuration; (b) Plan view of vertical configuration.

[Fig. 18(b)]. This design also provides the opportunity to install a geothermal heat exchange system into an open landfill which has been filled past 50% capacity, as installation does not take place until the landfill has reached around 75% of the maximum height. Starting GSHP operations with boreholes deeper within the waste will also allow for the implementation of more heat exchange loops while still maintaining proper operational spacing [Fig. 18(b)]. Most vertical configurations will require much less tubing than horizontal configurations of the same volume, also requiring less input energy to the circulatory pump [4,39,41–43]. Further, vertical arrangement of the heat exchange tubing will induce a consistent horizontal thermal profile within the waste, promoting uniform thermal settlement of the landfill. Vertical systems can also be optimized for the application of both heating and cooling [42]. A disadvantage of the vertical system in an open landfill is associated with the cost of drilling and installation. Similar to the vertical configuration in closed landfills, this layout is also not recommended for landfills that contain intermediate leachate or gas collection systems due to the potential of damaging these systems during drilling.

Horizontal heat exchange systems can also be implemented into new landfills where waste placement has yet to, or just begun. For landfills with large horizontal cross sections, horizontal loops can be installed at the top of each waste lift until reaching a nominal depth of 0.25, placing the heat exchange system within the optimal thermal zone [Fig. 19(a)]. For each horizontal cross-section, loops are organized in a parallel arrangement which requires much less energy input to the circulatory pump than loops placed in a series arrangement [43]. Additionally, two opposing master loops per lift will be installed to reduce the potential for differential settlement of the landfill [Fig. 19(b)]. The benefit of a horizontal system is a reduced initial cost due to easier installation processes than other heat exchange systems [39,43]. However, horizontal systems will require an increased time span for installation as each loop configuration must be installed following the placement of a new waste lift. Further, each horizontal set may be susceptible to damage during future placement and compaction of waste [43]. Gaps may also form between the heat exchange and MSW, reducing the thermal conductivity (and there for efficiency) of the system. Placing the horizontal loops within a compacted sand layer at each lift can reduce these effects.

For new landfills with less available area for heat exchange, horizontal loops can be coiled into an overlapping "slinky" configuration as shown in Fig. 20. By coiling the horizontal loops, the same amount of heat exchange can be accomplished in a smaller area, requiring less horizontal arrangements than needed from a standard horizontal loop configuration [4,39,43] [Fig. 20(a)]. Typically, the area required for similar thermal performance can be reduced by 20 to 30% [43]; however, the length of pipe required for installation may be increased by 100%, there for increasing initial costs. Due to the looping configuration and increased length of pipe needed, the required energy input to the circulatory pump is greatly increased compared to a typical horizontal loop configuration [39]. Installation of a "slinky" system is not recommended for landfills with larger available surface area, as this will increase the risk of differential settlement due to the development of uneven horizontal temperature profiles. Landfills required for both heating and cooling can benefit from "slinky" configurations due to the increased amount of heat exchange per unit area as the natural recharge of MSW temperature is not as necessary as for other GSHP systems [39,43].

One alternative to the use of HDPE or HDBE tubing for heat exchange is the use of copper tubing, referred to as a direct expansion (DX) or direct circulation system [43]. For direct

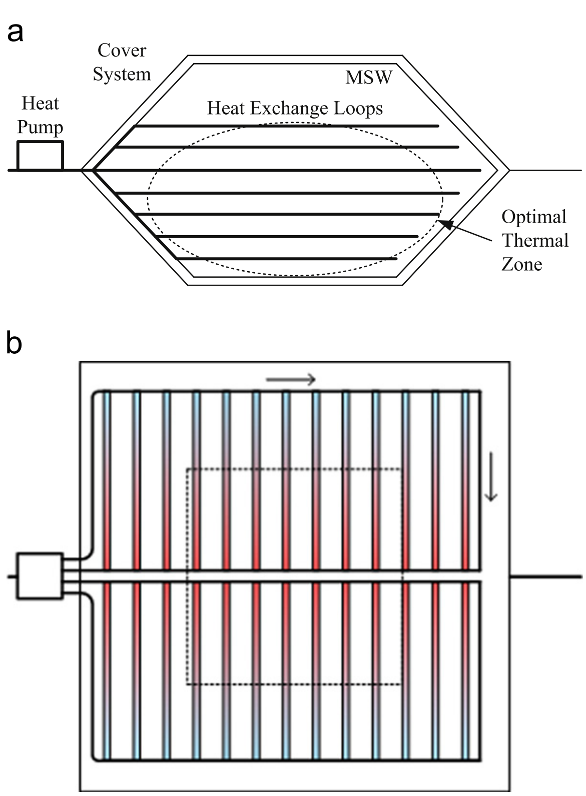

Fig. 19. Horizontal "loop" geothermal heat exchanger configuration for closed landfills: (a) Elevation section of vertical configuration; (b) Plan view of vertical configuration.

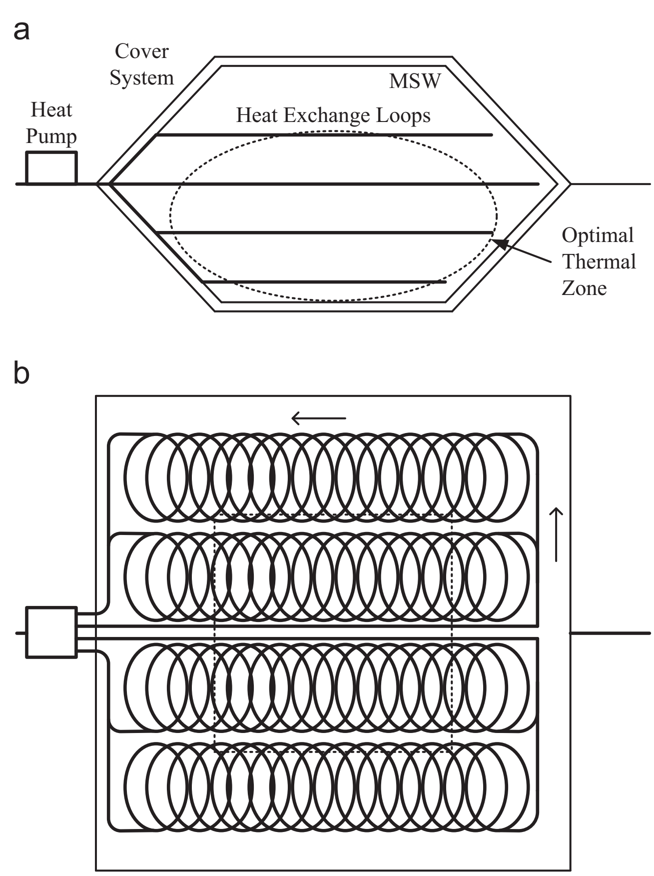

Fig. 20. Horizontal "slinky" geothermal heat exchanger configuration for closed landfills: (a) Elevation section of vertical configuration; (b) Plan view of vertical configuration.

circulation, the refrigerant from the heat pump system is directly circulated through the heat source or sink, there for eliminating the need for an additional heat exchange system to the heat pump. Direct expansion systems achieve a much higher efficiency than most other exchange systems due to the: increased thermal exchange properties of copper, reduced power input required to operate the system, and elimination of the ground-source heat exchange loop. However, the benefits of a direct expansion system can be outweighed by the increased cost of pipe material, and additional system design and environmental problems not encountered by other systems [42]. In the case of MSW landfills, the use of a direct expansion system may be affected by corrosion of the copper pipe when exposed to leachate within the MSW, although it is possible to account for this by using heavy grade pipe. The hydraulic barrier at the base of the landfill may alleviate environmental concerns associated with DX in borehole systems.

6. Cost analysis of geothermal heat exchange systems in landfills

6.1. Capital and recurring costs

According to Aswathanaryana et al. [44], the installation cost of geothermal systems depends primarily on the number and depth of heat exchanger wells or horizontal loops, the length and gauge of piping used, the temperature of the geothermal fluid, and access to electricity transmission lines. For geothermal systems installed in native ground, the capital cost of developing a geothermal system is about $650,000 per hectare based on industry standard estimates, including the cost of the heat pump(s) and transfer unit. The cost involved in drilling the wells generally accounts for half of the initial sunk cost. For installation of a geothermal system within a landfill in a horizontal "loop" configuration, the capital cost of developing a system is estimated to be less than $400,000 per hectare, again including the cost of the heat pump(s) and transfer unit. This estimate was derived by the authors based on experience with installation costs for horizontal landfill gas collection systems coupled with industry standard costs for geothermal system components; however, the literature provides no reference to previous installation of a landfill-based geothermal project. Annual operation and maintenance costs for geothermal systems are generally low at about 1% of total installation costs averaged over the project life [44].

6.2. Revenue sources, carbon credits, and tax incentives

The primary source of revenue from a geothermal system would be from sale of heat energy to nearby homeowners or businesses. In the U.S., it would potentially offset retail prices paid for heating via residential/commercial electric (nominally 12 cents per kW h in 2011) or natural gas (nominally four cents per kW h) systems. However, homeowners or businesses would need to be incentivized to convert to a geothermal system, and would be looking for compensation for the cost of modifying their existing heating systems (estimated to be on the order of $10,000–$15,000 for a typical single family home in the U.S., depending on the type and size of existing system). Structuring the long-term cost of heat supplied to homeowners would therefore be complex and subject to negotiation as part of a project. Some states have adopted a Renewable Portfolio Standard (RPS) for utilities to incentivize development of renewable energy projects. Through participation in a RPS, projects such as geothermal heat exchanger systems are eligible to earn and trade renewable energy credits (RECs) or carbon credits (because they offset carbon emissions from fossil fuel based energy production). In addition, a federal personal tax credit incentive of 30% of the total amount spent on installation of a geothermal heat pump system, up to a maximum of $2000, is available through 2016, which can be utilized if the geothermal system is used for residential systems.

6.3. Financial risks and potential ownership models

The primary financial risk associated with geothermal project development at landfills involves the availability of end users and their willingness to participate in a third-party contract for supply of heat energy, which would be contractually complex to ensure that all parties to an agreement are protected. Negotiating a long-term energy sale agreement with a cooperative association of end-users prior to project implementation would be prerequisite to obtaining project financing in the majority of cases. Other risks involved with developing geothermal heat exchangers at a landfill involve the potential for underestimating the amount of energy generated by the facility. To minimize this, a site-specific study for modeling waste characteristics and perennial internal temperatures is recommended, at least until landfill-based geothermal matures as a technology. The primary technical risks involved with geothermal project development involve equipment performance and construction challenges at active landfills, as development would involve close coordination between the geothermal construction crew, waste haulers, and the landfill operators.

A geothermal heat exchange system could be implemented in two main ways: self-development or development by an outside project developer. Alternatively, a landfill owner may consider developing the system in a hybrid manner. Under this model, the owner would develop the system within the landfill property, but only provide a central hookup connection point at the property boundary for transfer of an agreed quantity of heat energy over the life of the project to offsite end users. From there, a local utility company, homeowner cooperative, or other third party would manage all other aspects of the system.

7. Conclusions

This paper provides a thorough characterization of the thermal resource of landfilled municipal solid waste which can be implemented in geothermal heat exchange systems. Further, the potential impacts of heat exchange on methane generation, landfill liner performance and leachate collection system clogging are evaluated. Several geothermal heat exchange configurations for MSW landfills are presented for different operational and closure scenarios. Despite a dearth of case studies of landfill-based geothermal projects in the literature, a brief economic analysis of geothermal heat exchange in landfills indicates that this is a feasible and sustainable approach to implement into practice. Overall, it is concluded that landfills are a suitable resource for geothermal heat exchange.

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